Crack spacing in strained coatings on cohesive substrates

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Abstract

When natural and engineered systems are subjected to an applied strain-often driven by cooling or evaporation-the resulting stresses may lead to the formation of cracks. In many cases these cracks form patterns, which exhibit distinct length scales. The drying of mud is perhaps the classical natural example of this phenomenon [1]. In engineered systems, cracking patterns are observed in thin films. When thin glass strips are exposed to a thermal gradient [2] or thin colloidal suspensions are dried [3], uniformly spaced longitudinal cracks form parallel to the direction of the temperature or moisture gradient. Alternatively, when thin film coatings are subjected to the application of an axial strain transverse cracks, normal to the direction of the applied strain, form at regular intervals [4,5]. Fig. 1a shows cracks in a 160μm section of a TiN ceramic film on a steel substrate subjected to 2.56% axial strain. At a vastly different scale, similar transverse cracking patterns are a feature of asphalt concrete pavements systems in cold climates [6,7]. Typically, these cracks, driven by thermal shrinkage, form after an extreme cooling event. Fig. 1b illustrates a typical thermal cracking pattern observed on a 150m section (distance between construction joints) of interstate road in Minnesota [7]; these cracks formed in a single cooling event in the winter of 1996 when the surface pavement temperature dropped below -30^{o}C.

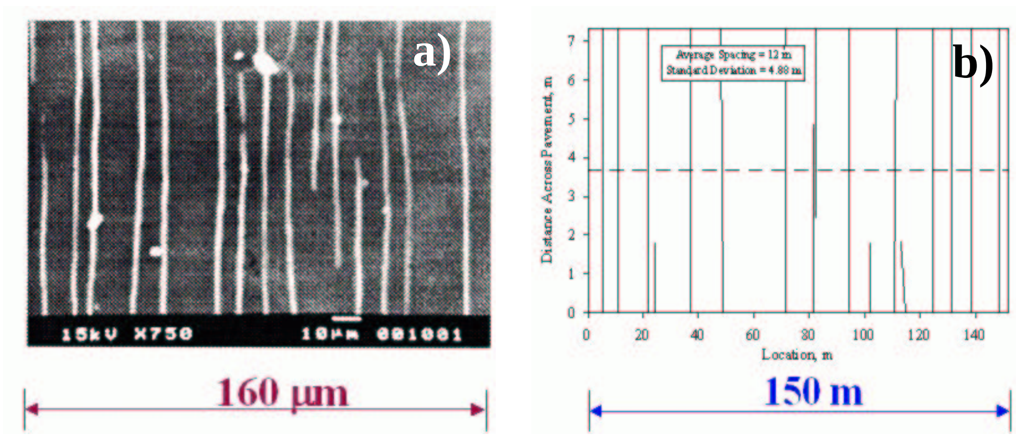

Figure 1: Cracking patterns in films subjected to axial strains: (a) TiN coating on a steel substrate [4]; (b) plan view of a cooled asphalt pavement resting on a granular subgrade [7]

In this paper, following recent work [5], a one-dimensional analytical solution for the stress distribution in a thermally shrinking a layer placed on an elastoplastic base is developed and validated by comparison with a 2D numerical solution. From the analytical model, a prediction of the length parameter that provides bounds on the thermal crack spacing is derived in terms of *cohesive*-frictional properties of the film-substrate interface. Predicted bounds on crack spacing are validated by comparison with field observations on asphalt pavements in cold climates.

It is demonstrated that the proposed formulation can also be applied to estimate the average crack density observed in thin ceramic films subjected to the application of an axial strain; in the latter system, the crack spacing is six decades smaller than that observed in pavement systems. On the basis of the 1D model a simple, yet effective "pull-out" test is proposed for thin films. In this test, the *cohesive properties* of the film-substrate interface are deduced *directly* from the evolution of the crack spacing with increasing applied strain.

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